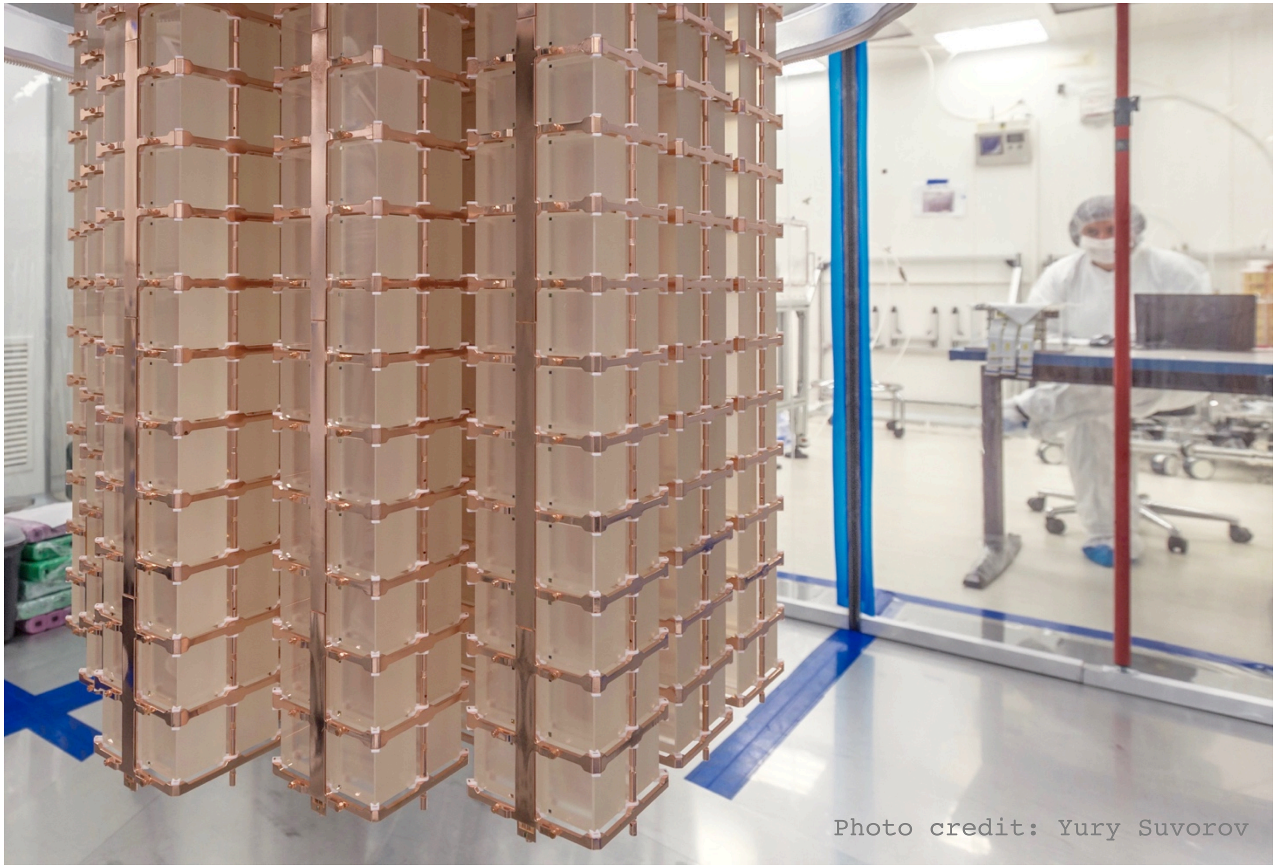
The start up of the CUORE experiment at LNGS

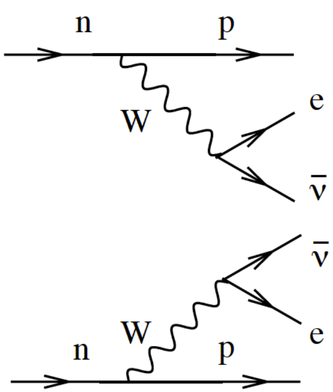


Antonio Branca @ INFN Padova
On behalf of the CUORE Collaboration

WIN2017 @ UC Irvine – 19-24 June 2017

Double beta decay (DBD)

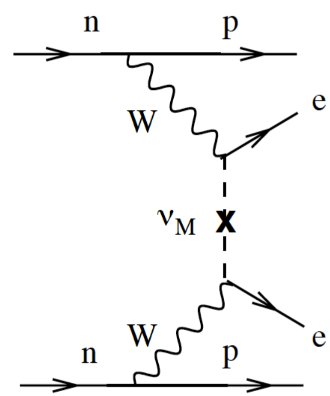
2ν DBD: $(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}$



- proposed in 1935 by Maria Goeppert-Mayer;
- 2nd order process allowed in the Standard Model;

$$\tau \sim 10^{19-21}\, yr$$

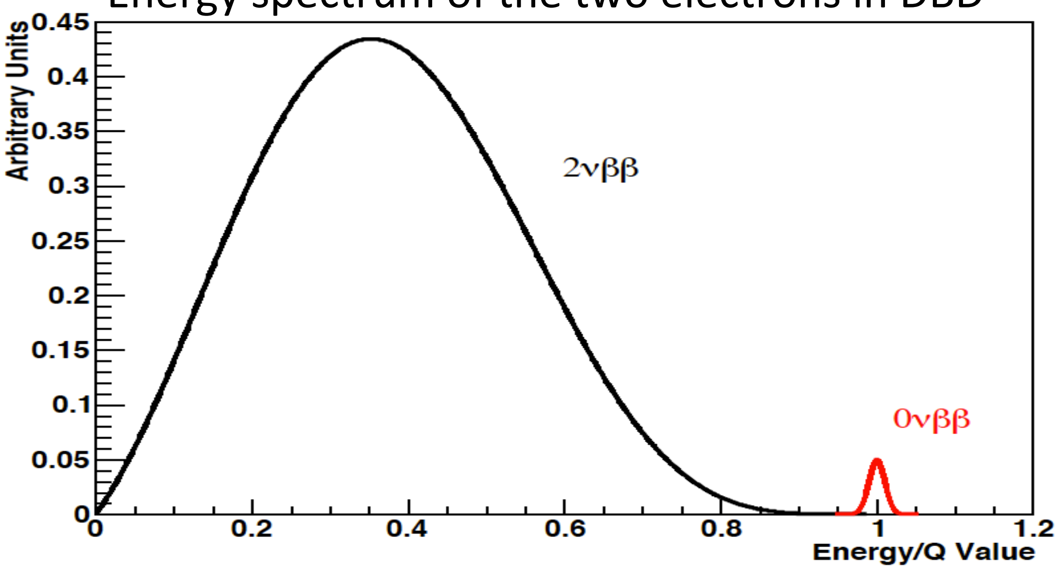
0ν DBD: $(A,Z) \rightarrow (A,Z+2) + 2e^{-}$



- proposed in 1937 by Ettore Majorana;
- requires physics beyond Standard Model;

$$\tau > 10^{24-25}\, yr$$

Energy spectrum of the two electrons in DBD



0ν DBD Signature: monochromatic line in the energy spectrum at the energy value

$$Q_{\beta\beta} = M_p - (M_d + 2\, m_e)$$

smeared by detector resolution!

Double beta decay (DBD) II

The 0ν DBD half-life:

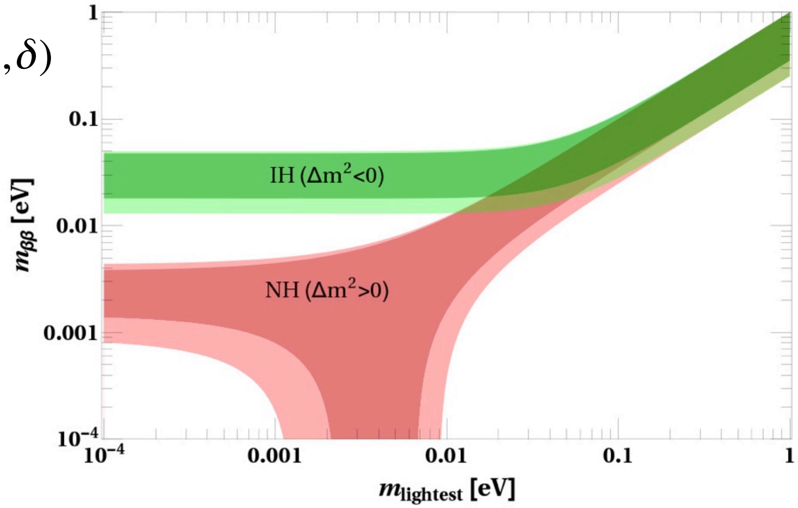
Effective Majorana mass

$$m_{\beta\beta} = f(\Delta m_{1,2}, \Delta m_{2,3}, m_1, \alpha_1, \alpha_2, \delta)$$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\, |M^{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

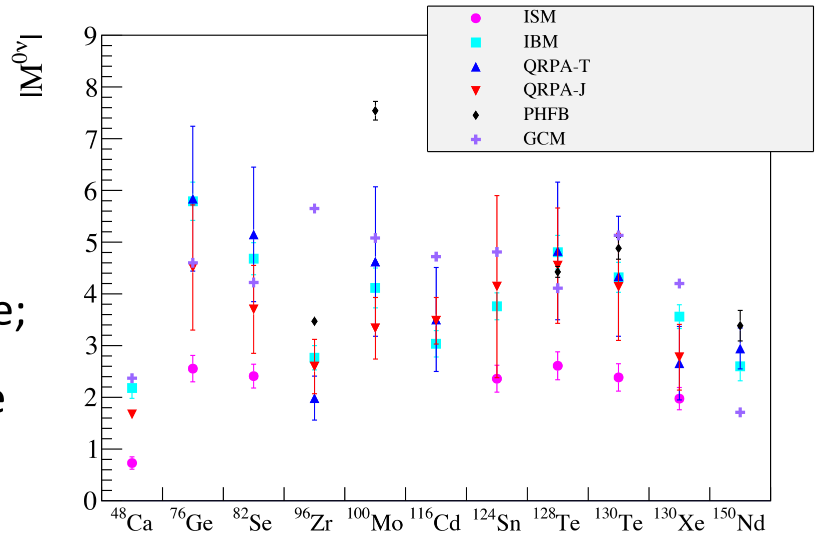
Phase space factor ~$Q^5_{\beta\beta}$ (accurately calculable)

Nuclear Matrix Element (theoretical uncertainty ~2-3)



Physics consequences if 0ν DBD is observed:

- proof of the Majorana nature of neutrino;
- constrain on the neutrino mass hierarchy and scale;
- lepton number violation (ΔL = 2): a possible source of matter-antimatter asymmetry in the universe;



Sensitivity

Half-life corresponding to the minimum number of detectable signal events above background at a given C.L.

Isotopic abundance

Detector mass

Measuring time (also "live time")

$$\left(T_{1/2}^{0\nu}\right)^{sens.} \propto i.a. \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

Background

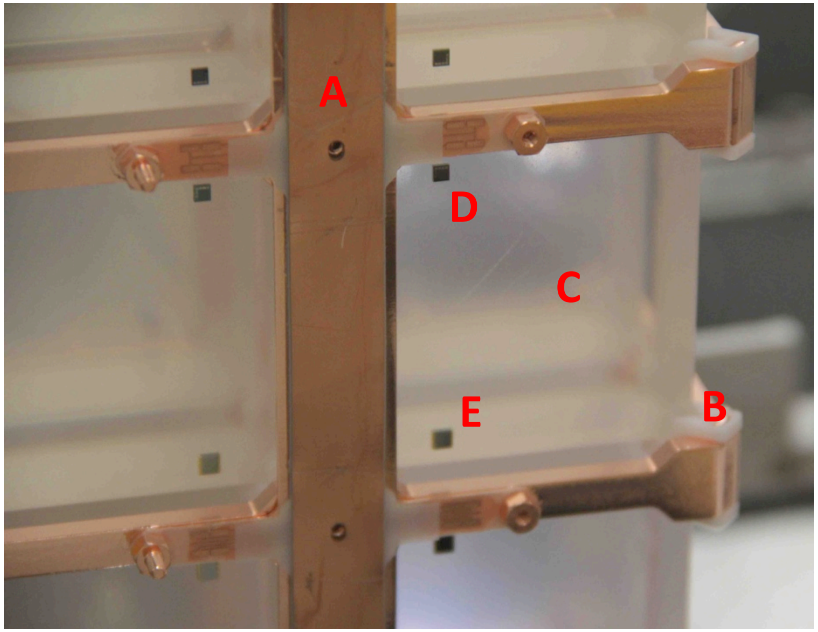
Detector efficiency

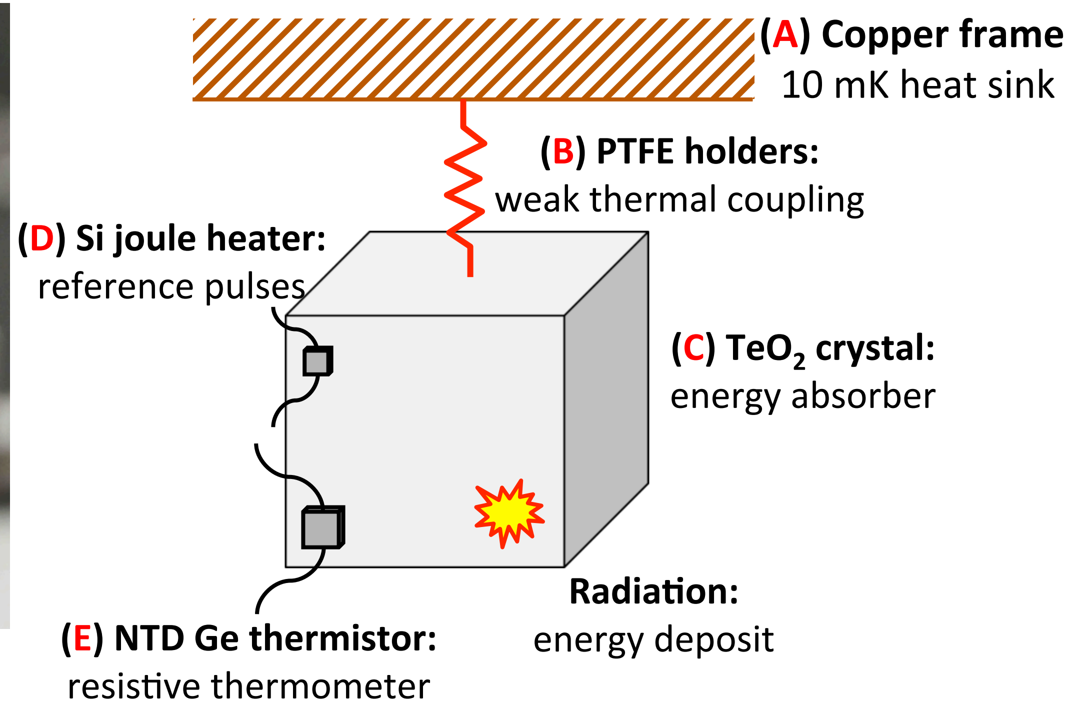
Energy resolution

In order to build a high sensitivity experiment:

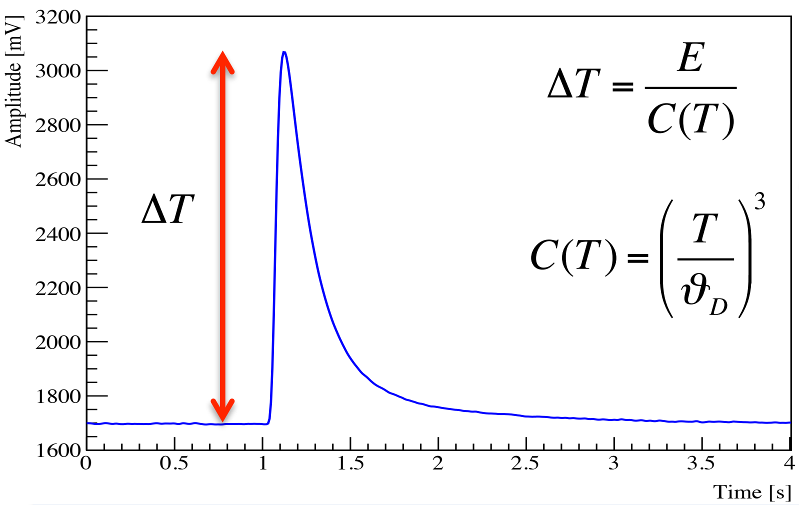
- select 0v DBD candidates with high natural isotopic abundance or enriched;
- high detector mass;
- good detector stability over a long period;
- extremely high energy resolution;
- extremely low background environment;

Bolometric technique in CUORE





readout



$$\Delta T = \frac{E}{C(T)}$$

$$C(T) = \left(\frac{T}{\vartheta_D}\right)^3$$

Bolometer: detector and source of 0ν DBD. High efficiency and resolution;

Low temperature needed:

$$@T = 10mK \Rightarrow \quad C \sim 10^{-9}\frac{J}{K}; \quad \Delta T = 0.1\frac{mK}{MeV}; \quad \tau \sim 1s;$$

A rare event search

Searching for a rare event (0ν DBD): $\tau > 10^{24-25}\, yr$

Extremely important to reduce as much as possible backgrounds:

a. natural radioactivity from outside the detector:

- cosmic ray muons induced background;
- neutron and gamma fluxes;

REDUCTION: underground laboratories and shielding

b. natural radioactivity from the detector itself:

- long-lived nuclei (^{40}K, ^{238}U, ^{232}Th);
- anthropogenic radioactive isotopes (^{60}Co, ^{137}Cs, ^{134}Cs);
- cosmogenical radioactive isotopes (^{60}Co);

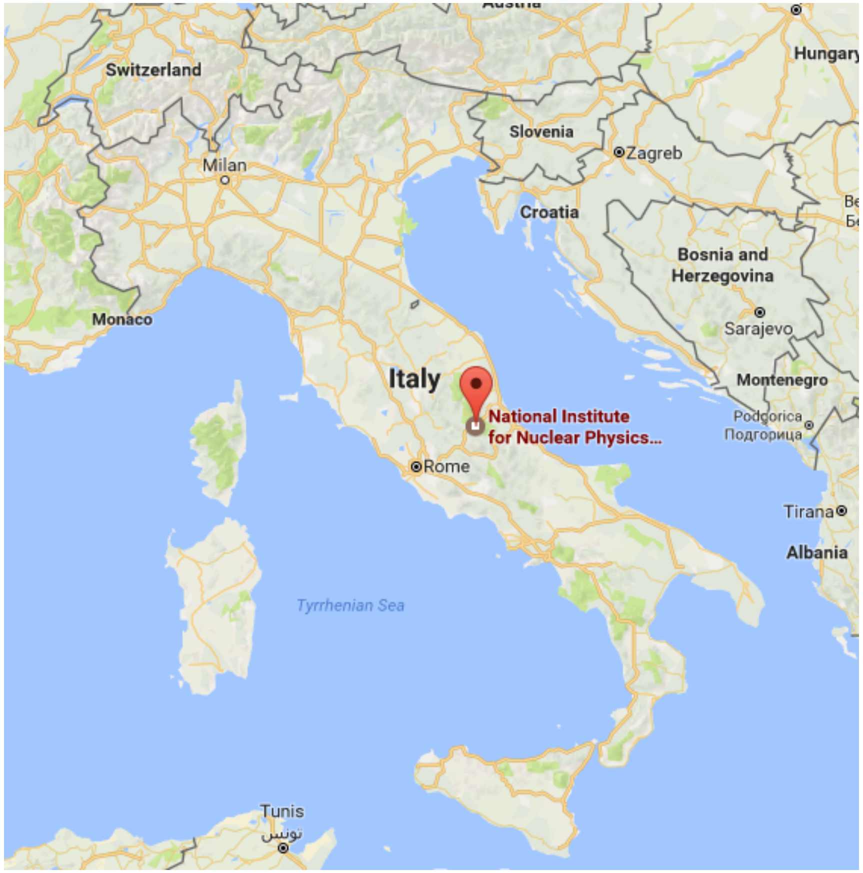
REDUCTION: material selection and cleaning techniques

c. mechanical vibration noise:

- cryogenic system and seismic noise;

REDUCTION: suspension and damping systems

CUORE installed @ LNGS



- average depth: ~3600 m.w.e.
- muon flux: $\sim 3\times10^{-8}\ \mu/(\mathrm{s\ cm^2})$
- neutron flux: $< 4\times10^{-6}\ \mathrm{n/(s\ cm^2)}$
- gamma flux: $\sim 0.73\ \gamma/(\mathrm{s\ cm^2})$

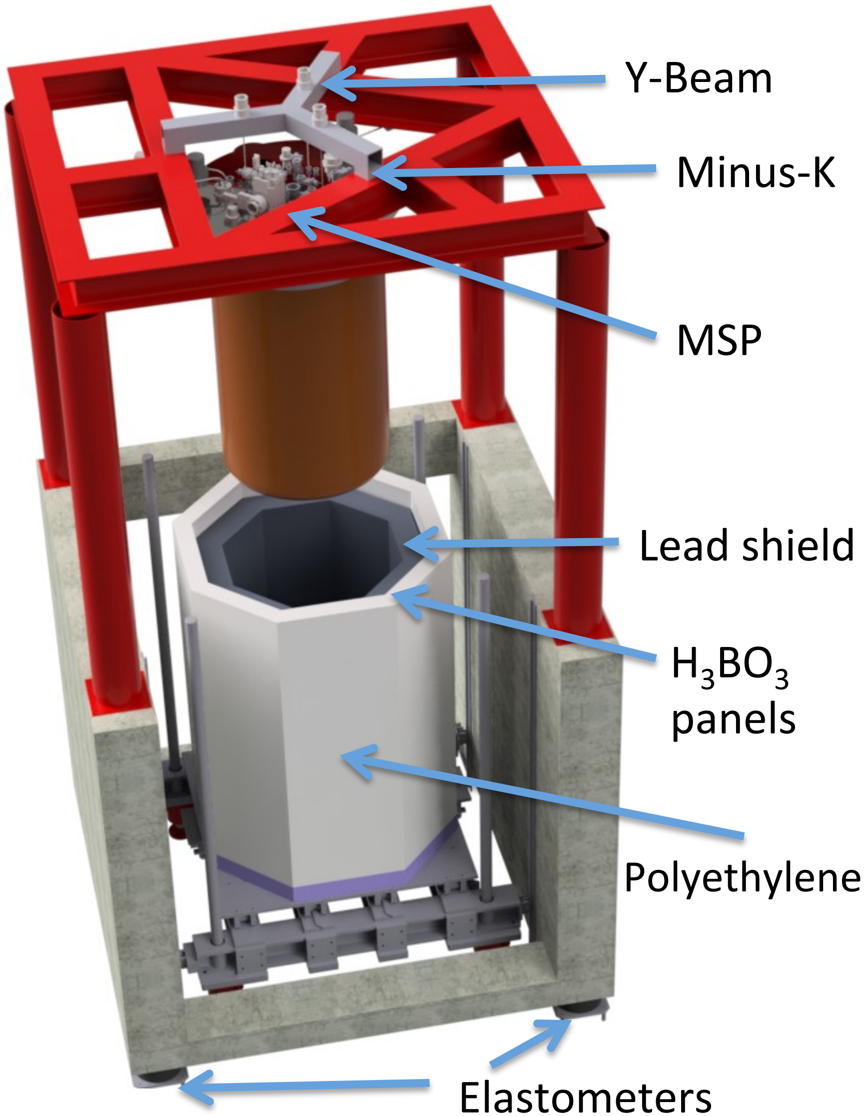
Suspension System

Abatement of vibrations: detector mechanical decoupling from the outside environment:

- detector hung by the Y-Beam through cables made of stainless steel tie bars, Kevlar ropes and copper bars (damping the horizontal oscillations);
- 3 minus-K springs connect the Y-Beam to the Main Support Plate, MSP (attenuating the noise of ~35 dB);
- elastometers at the structure basis (seismic isolators);

Radioactive background reduction:

- outer neutron shield: polyethylene + borated powder;
- outer gamma shield: lead shield;



Cryogenic System

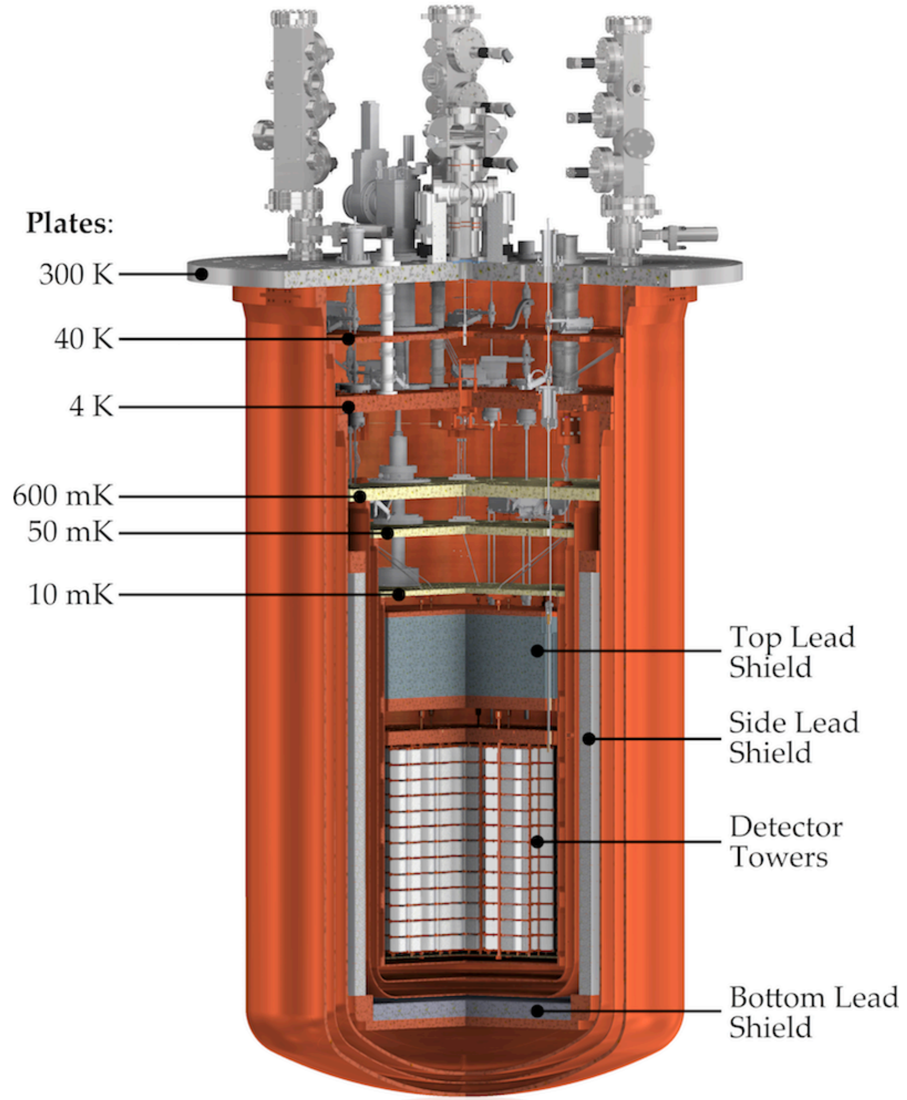
Specifics:

- Fast Cooling System: T down to ~40 K;
- 5 Pulse Tubes cryocooler: T down to ~4 K;
- Dilution Refrigerator: T operations 10 mK;
- Nominal cooling power: 3 μW @ 10 mK;
- Cryogen-free cryostat: high duty cycle;

Cool down ~15 tons @ T < 4 K and ~1.5 tons @ T = 10 mK in a few weeks.

Radioactive background reduction:

- material screening and accurate selection to ensure radiopurity;
- lead shielding (Roman and modern Pb);



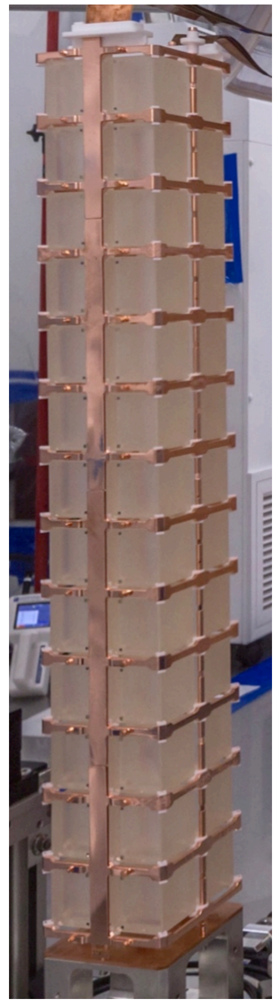
The CUORE "core"

988 TeO_2 crystals arranged in 19 towers (13 floors - 52 crystals each):

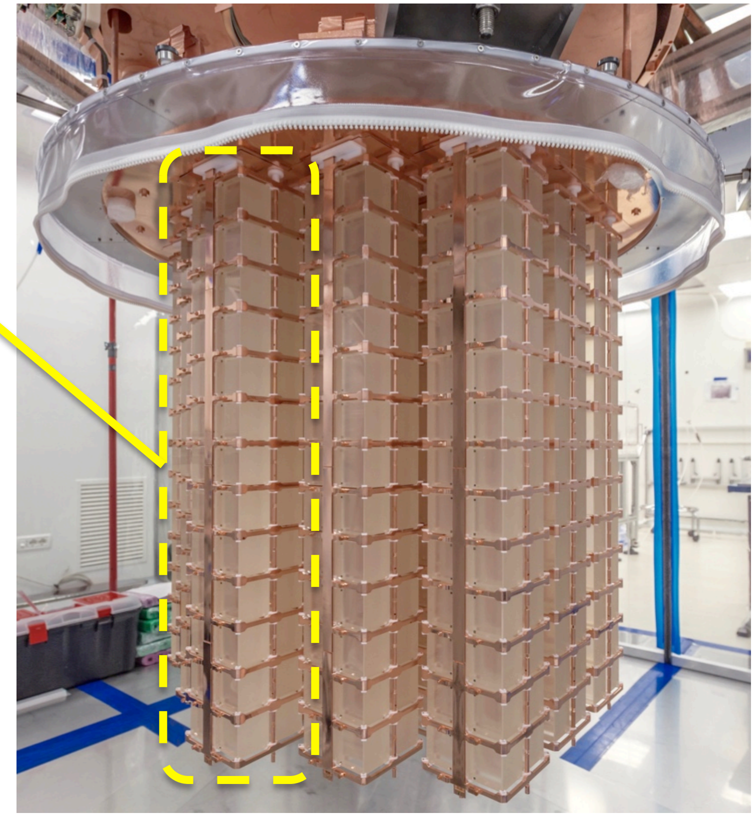
- ^{130}Te for 0ν DBD: good Q-value (2528 keV) in low β/γ region, high natural abundance (34.17%);
- total TeO_2 mass of 742 kg (206 kg of ^{130}Te);

Radioactive background reduction:

- minimization of material/ surface facing the crystals;
- developed a stringent protocol for the tower assembly and material cleaning (tested on predecessor **CUORE-0**);



A single CUORE tower

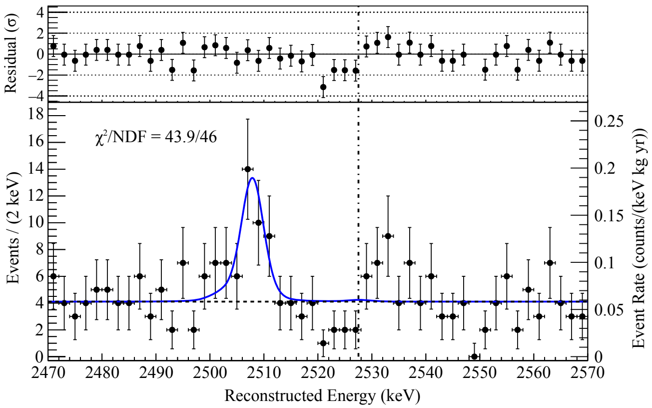


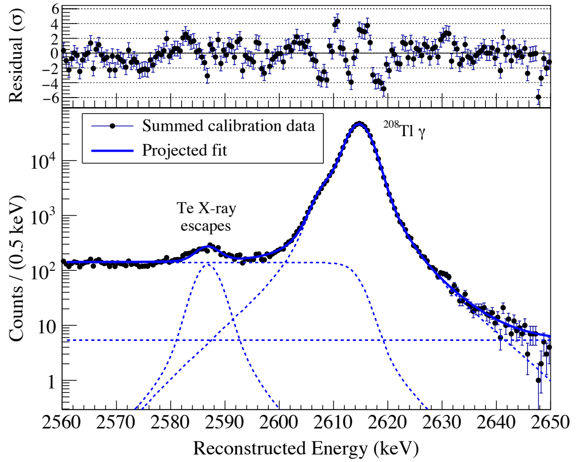
All 19 towers installed between July-August 2016

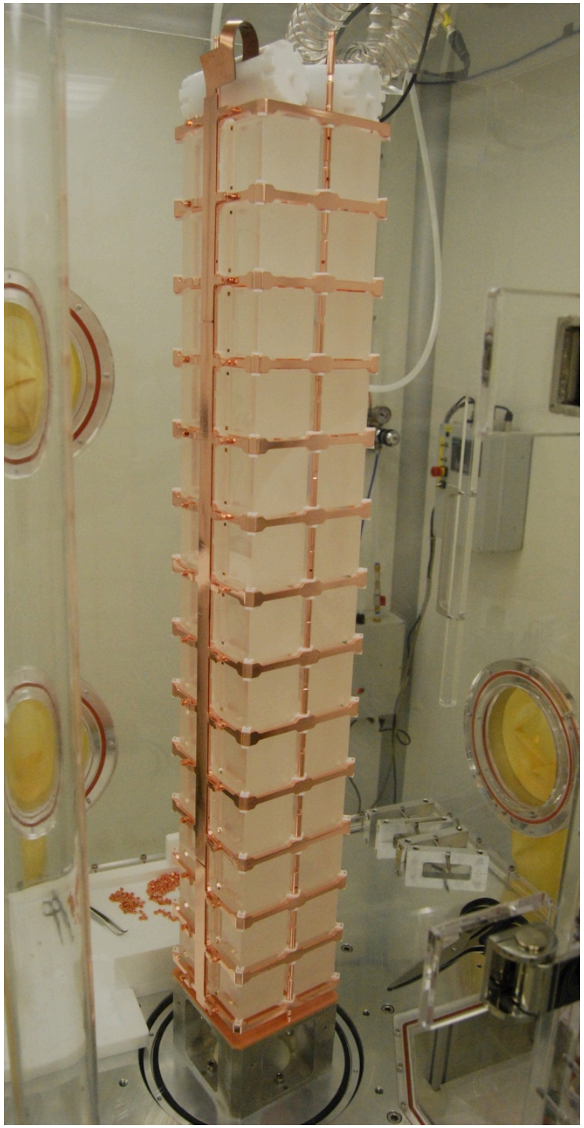
CUORE0: the first CUORE tower

First detector tower built using the new techniques and assembly line developed for CUORE:

- operated from 2013 to 2015 in old Cuoricino cryostat;
- proof of concept for CUORE;
- 0ν DBD search by itself;







RESULTS:

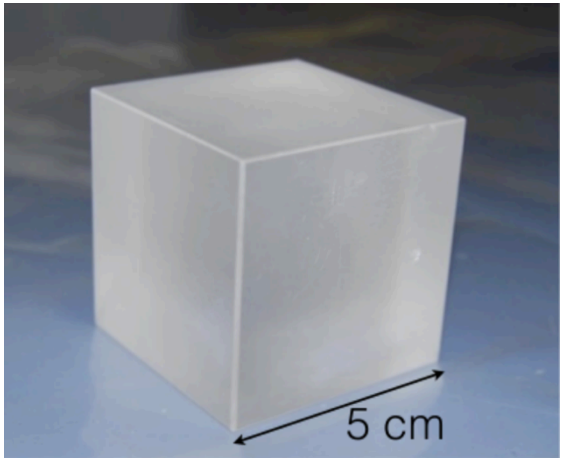
- ➢ 0νββ upper limit: $T_{1/2}(0\nu) > 4\times10^{24}$ yr (@ 90% C.L.) combined CUORE0 + Cuoricino results;
- ✓ ROI background: 0.058 ± 0.004 c/(keV•kg•yr);
- ✓ Resolution: 5.1 ± 0.3 keV FWHM @ 2615 keV;

Resolution consistent with the CUORE goal of 5 keV.

Material cleaning and assembling

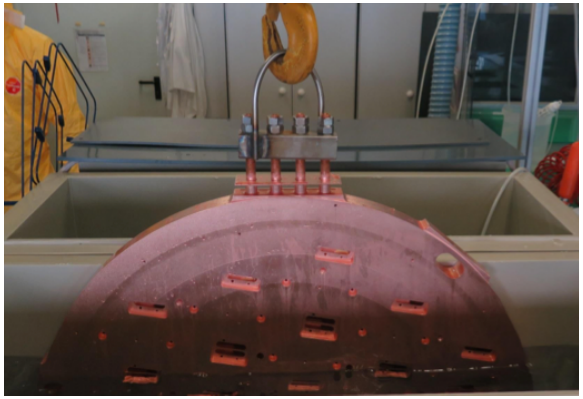
Production of the TeO_2 crystals:

- by Shanghai Institute of Ceramics, Chinese Academy of Science (SICCAS);
- two successive crystal growths starting from high purity synthetized TeO_2 powder;
- cutting, orienting and shaping from raw ingots and surface polishing and packaging;
- all operations performed in a dedicated clean room and following strict controls to limit radioactive contamination;



Cleaning of copper surfaces (tower parts and 10 mK cryostat shield):

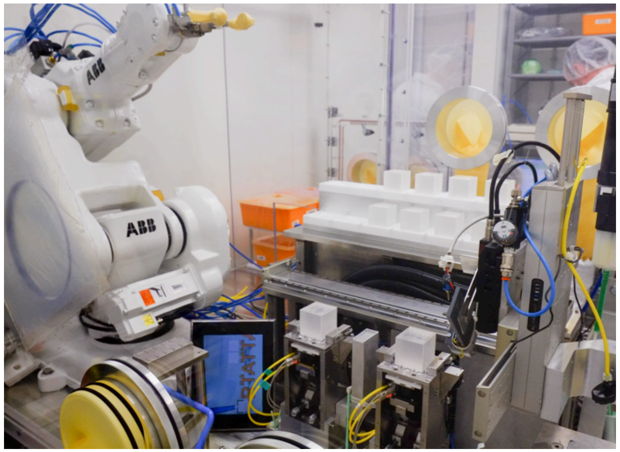
- new cleaning techniques developed at LNL;
- tumbling, electropolishing, chemical etching, magnetron plasma aimed at the removal of a thin layer of material (from 1 µm to 100 µm);



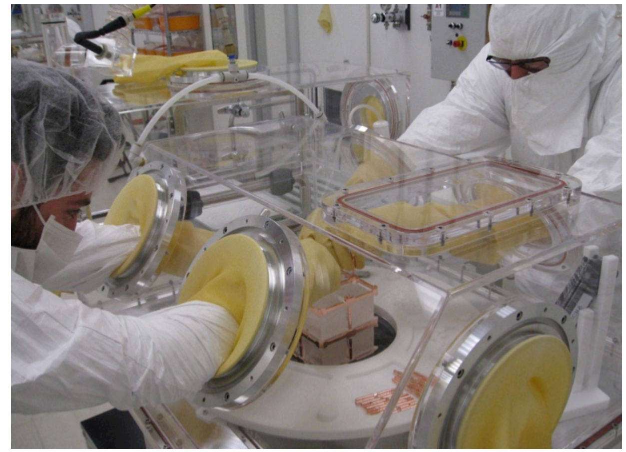
Material cleaning and assembling

Strict protocol adopted for each step of the CUORE towers construction: all in N_2 atmosphere and within glove boxes to avoid radioactive recontamination;

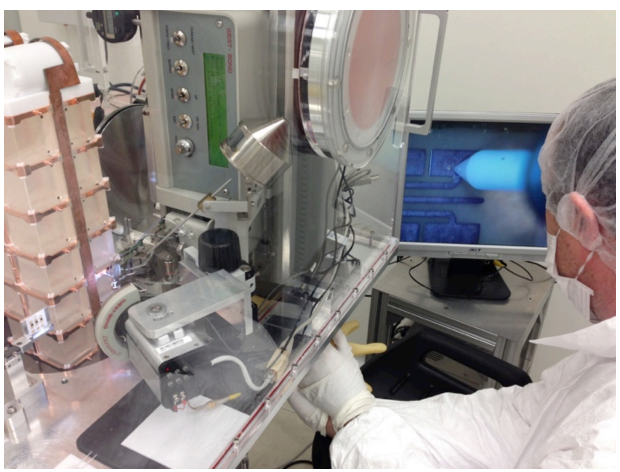
1. sensors gluing



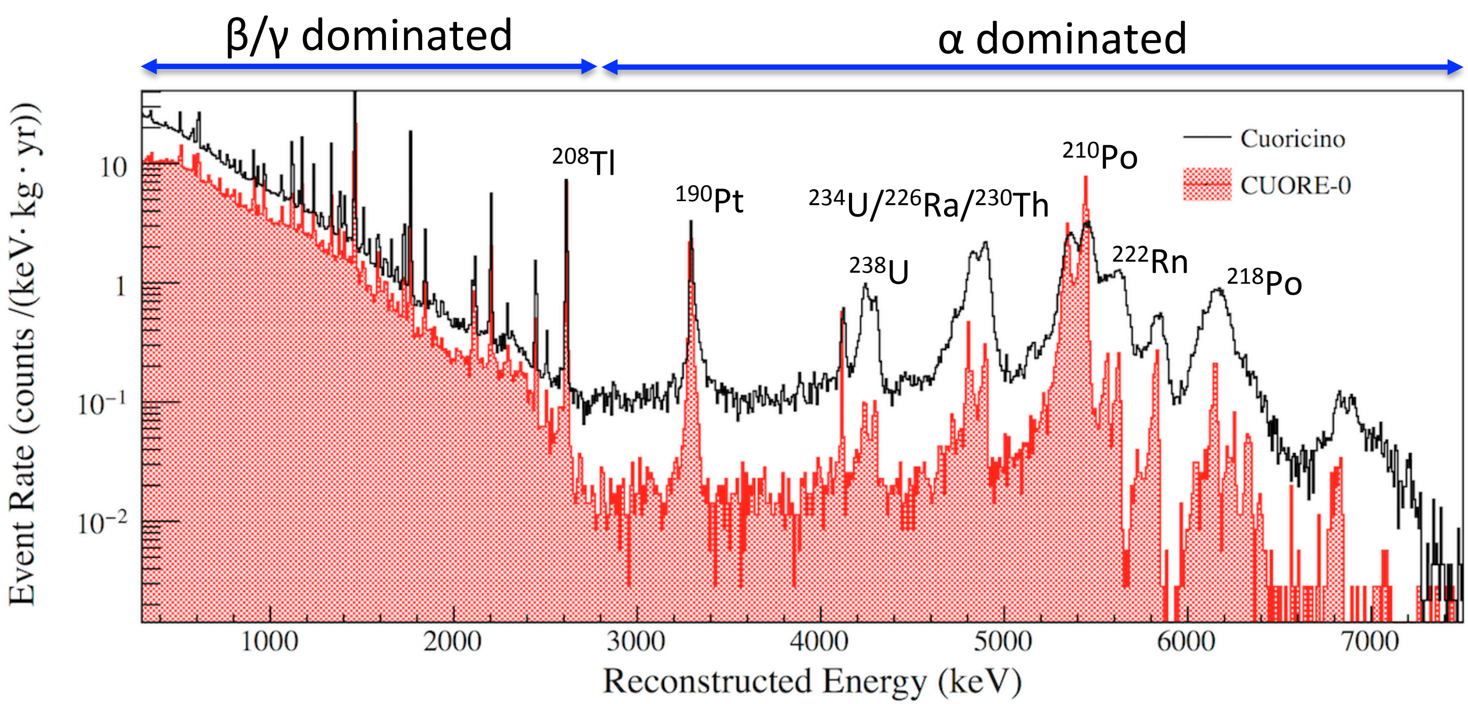
2. tower assembly



3. wire bonding



4. tower storage



Comparison of the background in Cuoricino and CUORE-0

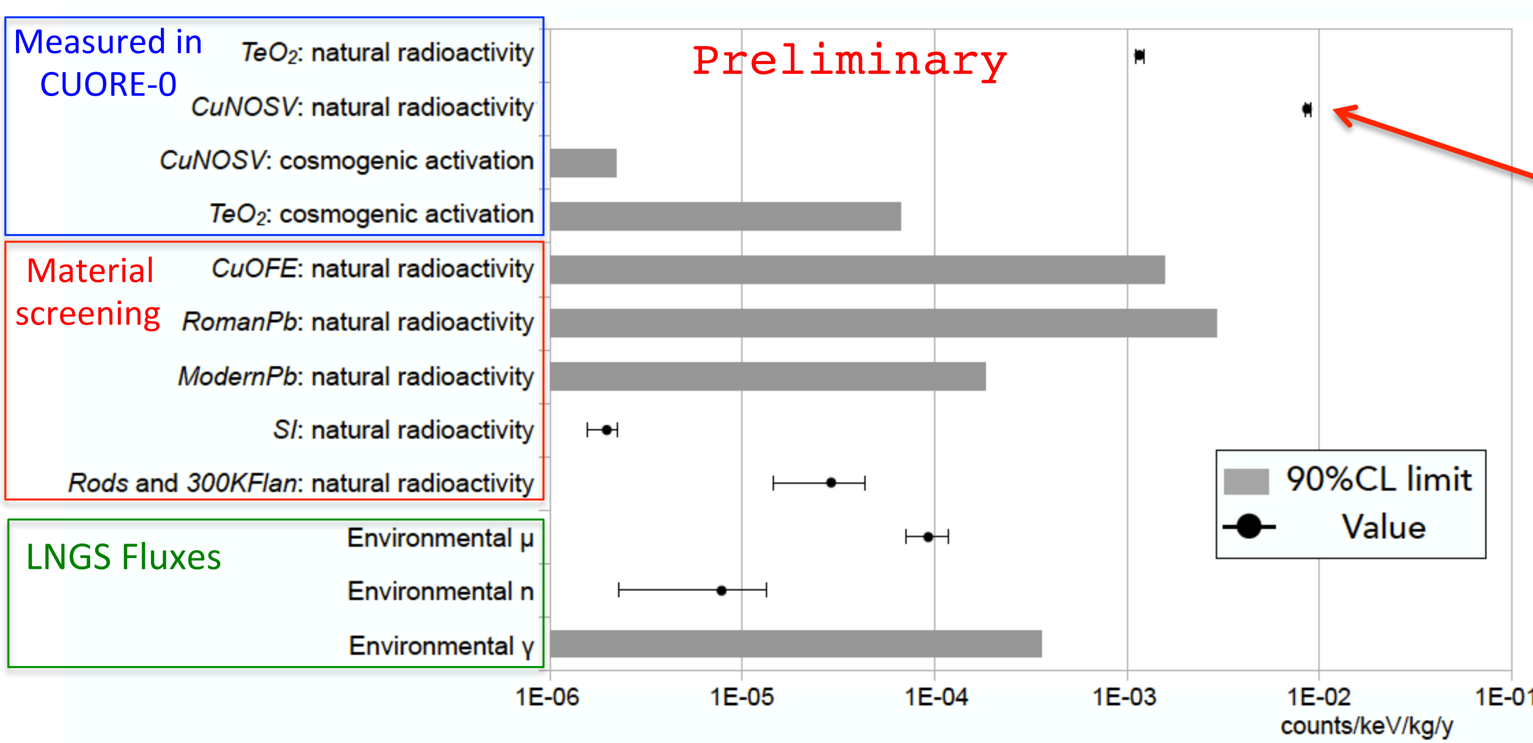
Background indexes (counts/(keV•kg•yr))

	0ν DBD region (2.47-2.58 MeV)	α region (2.7-3.9 MeV)
Cuoricino	0.169 ± 0.006	0.110 ± 0.001
CUORE-0	0.058 ± 0.004	0.016 ± 0.001

- Material cleaning: ^{238}U and ^{232}Th α lines reduced (~ factor of 7);
- Tower assembly in N_2 atmosphere: ^{238}U γ lines reduced (~ factor 2/3);
- Same Cuoricino cryostat: ^{232}Th γ lines not reduced;

CUORE background projection

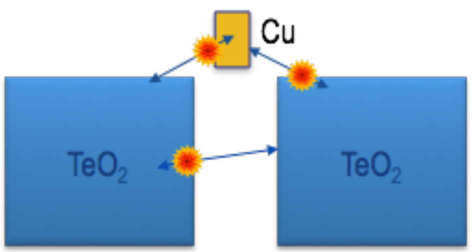
Main background index in the 0ν DBD region expected for the various components of CUORE



expected dominant contribution from the Cu of the towers structure

Projected total BI in the 0ν DBD region is consistent with CUORE background goal (10^{-2} counts/(keV•kg•yr)):

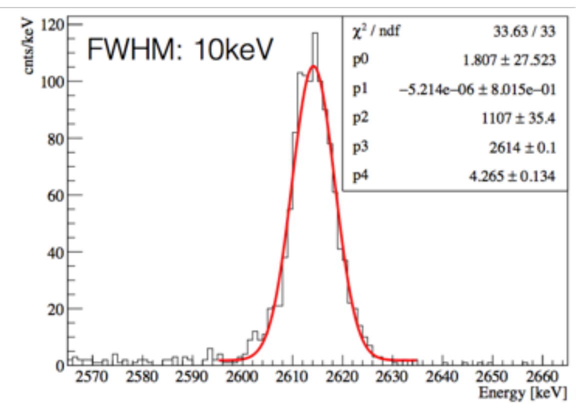
$$BI = (1.02 \pm 0.03(stat.)^{+0.23}_{-0.10}(syst.)) \cdot 10^{-2} \frac{counts}{kev \cdot kg \cdot yr}$$ (Preliminary)

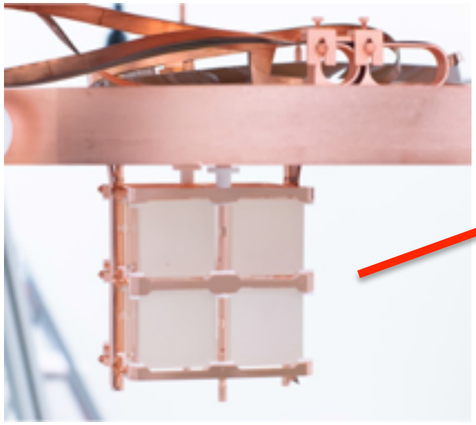


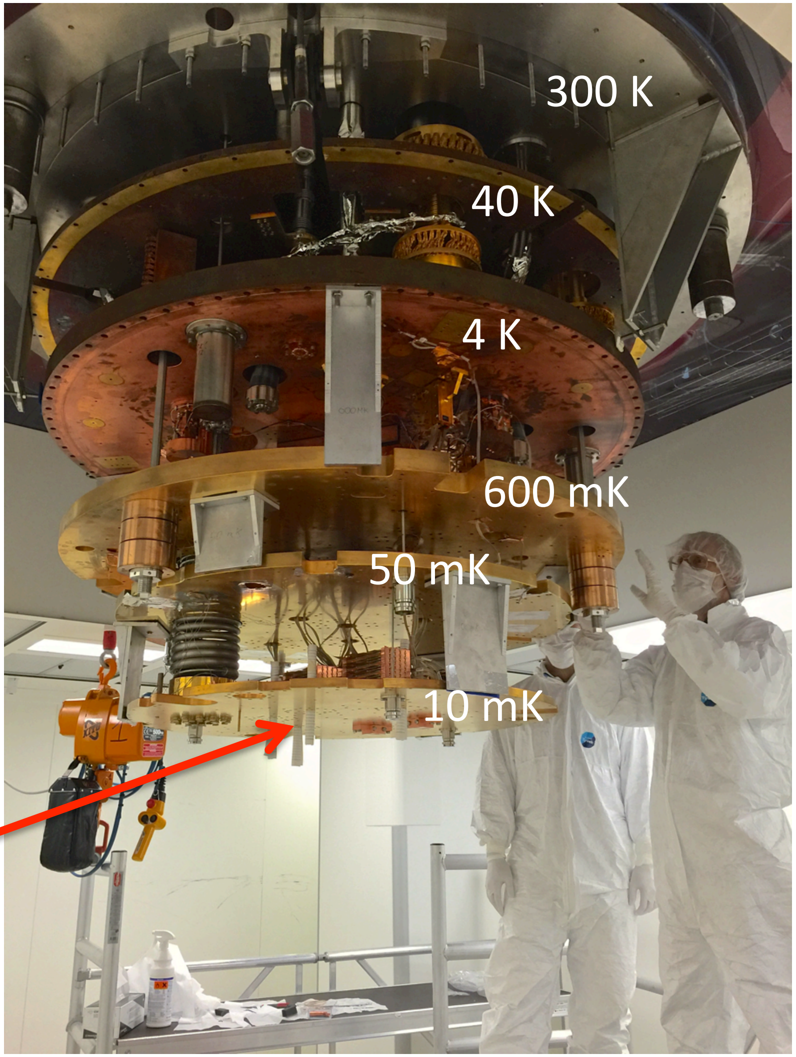
Cryostat commissioning

Commissioning completed in March 2016:

- stable base T = 6.3 mK over 70 days (no detector, full load);
- full detector read-out chain (electronics, DAQ) test, temperature stability with Mini-Tower (8 crystal tower);



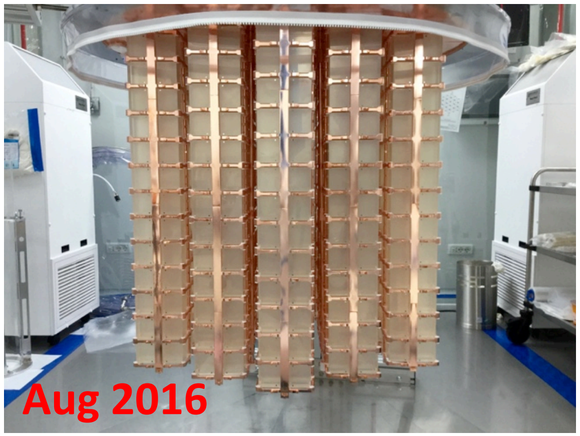




Mini-Tower resolution without noise optimization.

CUORE Installation

Towers installation completed



Aug 2016

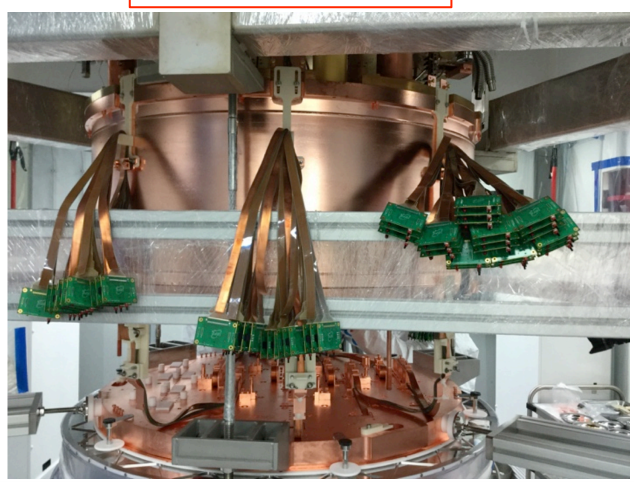
10 mK Cu shield closed

Lead shield installed

Cryostat closed

Nov 2016

Cables routing



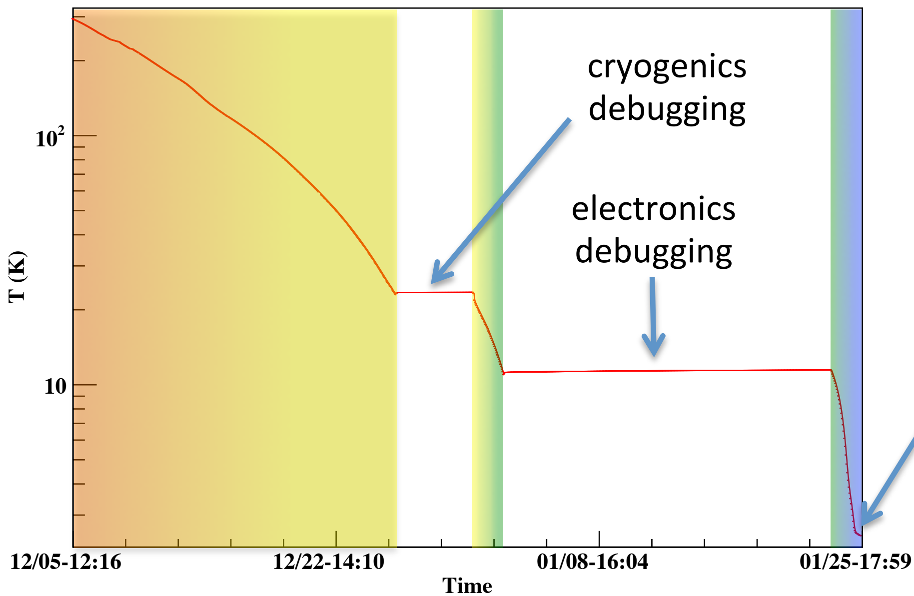
Sep – Nov 2016

CUORE cooldown and commissioning

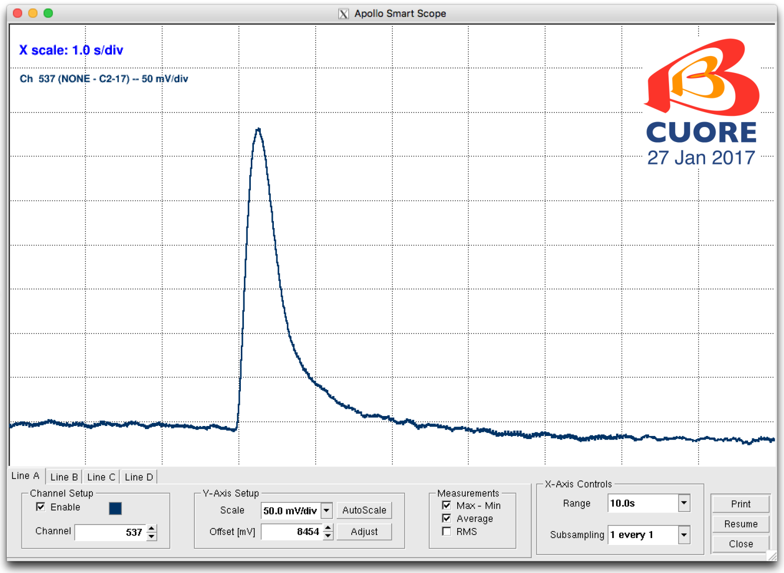
- cooldown started on Dec 5, 2016;
- lasted about 3.5 weeks (without taking into account technical stops for system debugging);
- on Jan 26, 2017 reached a base temperature of T = 7 mK;

After the cooldown started a phase of detector optimization

Diode thermometer at 10mK plate



First pulse observed on Jan 27, 2017



CUORE status

Noise optimization:

- electronic noise attenuation;
- reduction of mechanical vibration;
- tuning of the pulse tube relative phase shifting;

Temperature scan:

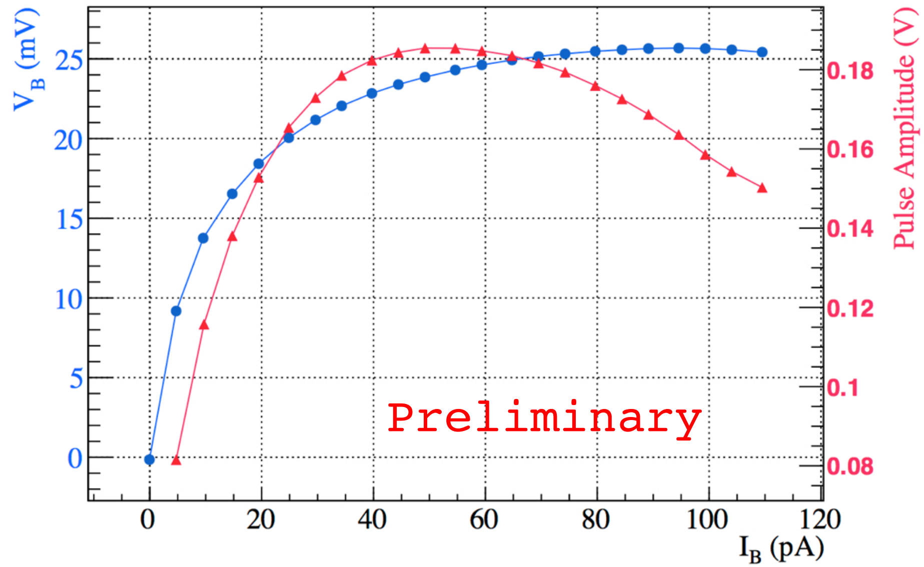
- scan around the base temperature (T_{base}) to choose the value optimizing the signal and to set the design thermistors' value of the resistance;

Working point measurement:

- current bias (I_B) scan to choose the value maximizing the SNR for each thermistor at the given T_{base};

Commissioning of the analysis software;

CUORE started taking data on April 2017

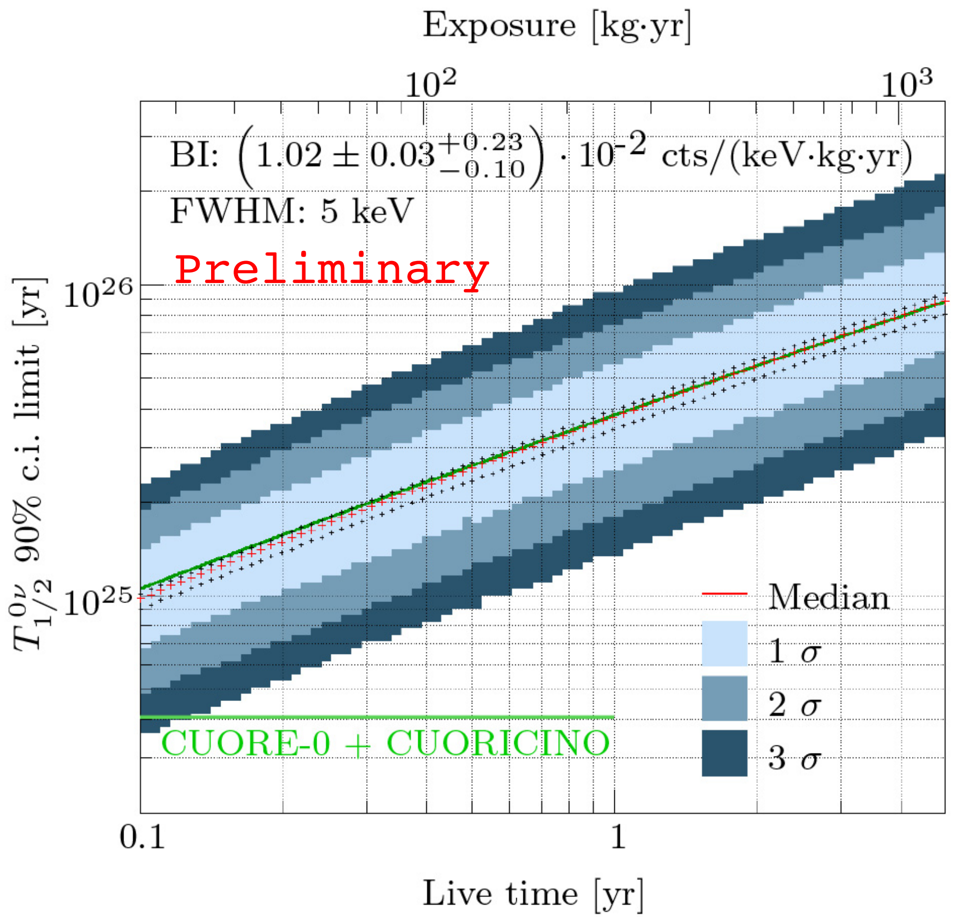


"Neutron Transmutation Doped" (NTD) Germanium thermistors to read-out the crystals

$$R_{th} = R_0 e^{\sqrt{\frac{T_0}{T_{base}}}} = \frac{V_{th}}{I_B}$$

Projected exclusion sensitivity

- Bayesian fit on toy MC background spectra;
- exclusion sensitivity obtained from the distribution of the 90% C.I. limits on $T^{0\nu}_{1/2}$ for the toy MC experiments for each fixed live time;
- values of the BI projection for CUORE and energy resolution from CUORE-0 have been considered as input for the computation;



RESULTS:

✓ expected to reach CUORE-0 + Cuoricino sensitivity in few days;

✓ expected exclusion sensitivity of $T^{0\nu}_{1/2}$~ 9×10^{25} yr (90% C.I.) in 5 years of live time;

Conclusion

- November 2016: installation completed;
- Dec 2016 – Jan 2017: successful cooldown of the detector;
- 27 Jan 2017: first CUORE pulse;
- Feb – Apr 2017: commissioning of the detecor;
- April 2017: CUORE started taking data;

Thank you for your attention!

Additional material

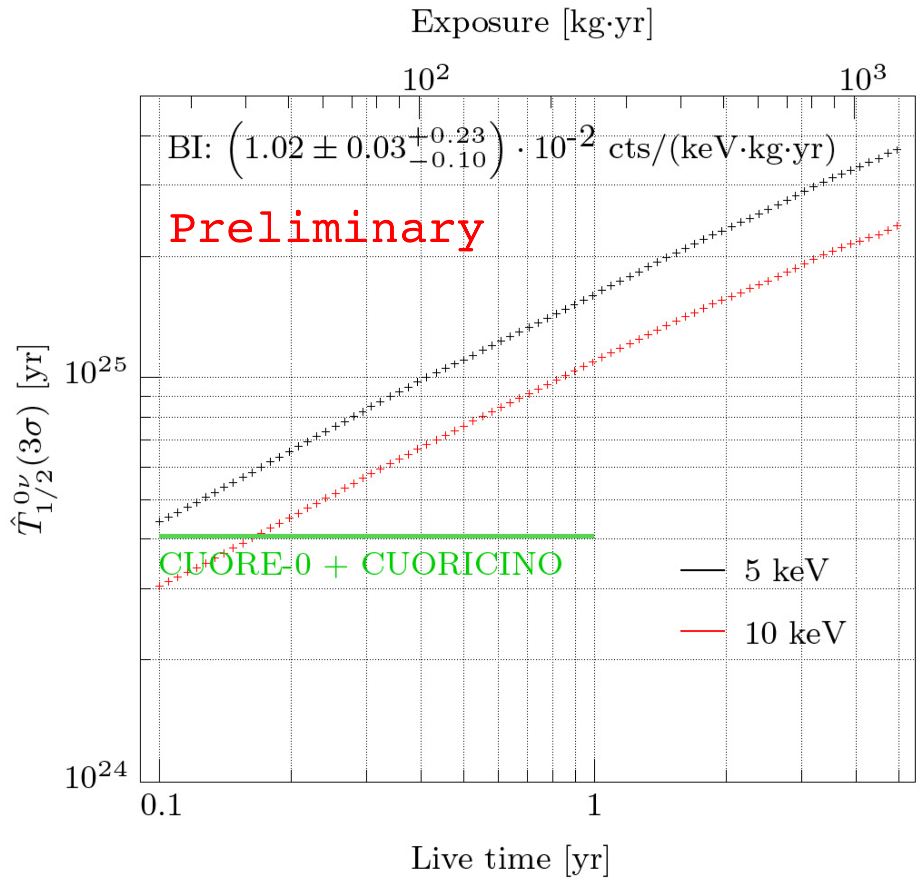
List of useful papers

CUORE Collaboration results in this presentation:

- Production of high purity TeO_2 single crystals for the study of neutrinoless double beta decay, J. Cryst. Growth 312 (2010) 2999-3008;
- Validation of techniques to mitigate copper surface contamination in CUORE, Astropart. Phys. 45 (2013) 13-22;
- Search for Neutrinoless Double-Beta Decay of Te-130 with CUORE-0, Phys. Rev. Lett. 115, 102502 (2015);
- Analysis Techniques for the Evaluation of the Neutrinoless Double-β Decay Lifetime in Te-130 with CUORE-0, Phys. Rev. C 93, 045503 (2016);
- The projected background for the CUORE experiment, arXiv:1704.08970;
- CUORE Sensitivity to $0\nu\beta\beta$ Decay, arxiv:1705.10816;

Projected discovery sensitivity

- Bayesian fit on toy MC background spectra;
- discovery sensitivity obtained from $T^{0\nu}_{1/2}$ for which the posterior probability of the background only hypothesis given the data is smaller than 0.0027 (i.e. 3σ) in 50% of the experiments;
- values of the BI projection for CUORE and energy resolution from CUORE-0 have been considered as input for the computation. Also a worse scenario, with 10 keV FWHM, has been considered;

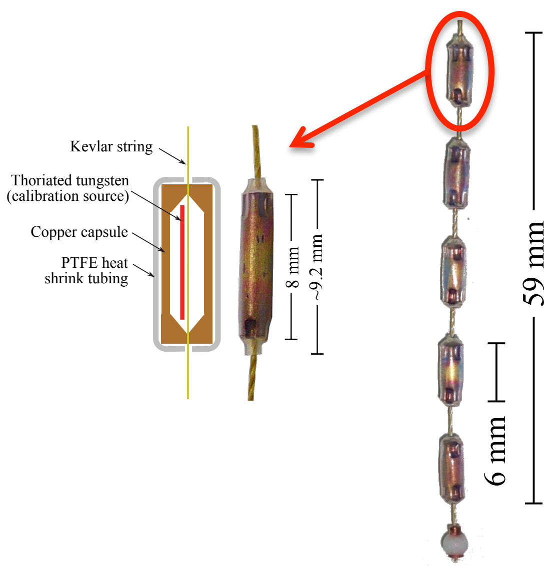


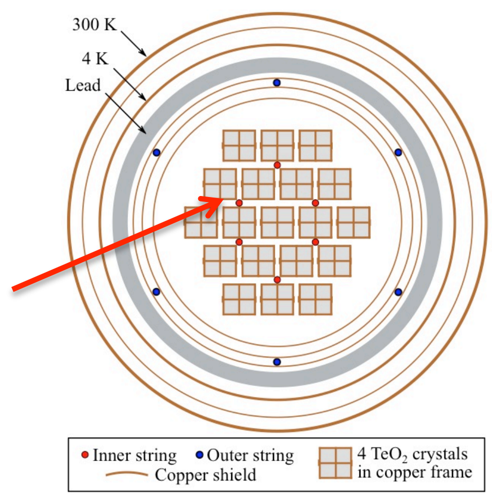
RESULTS @ 5 keV FWHM:

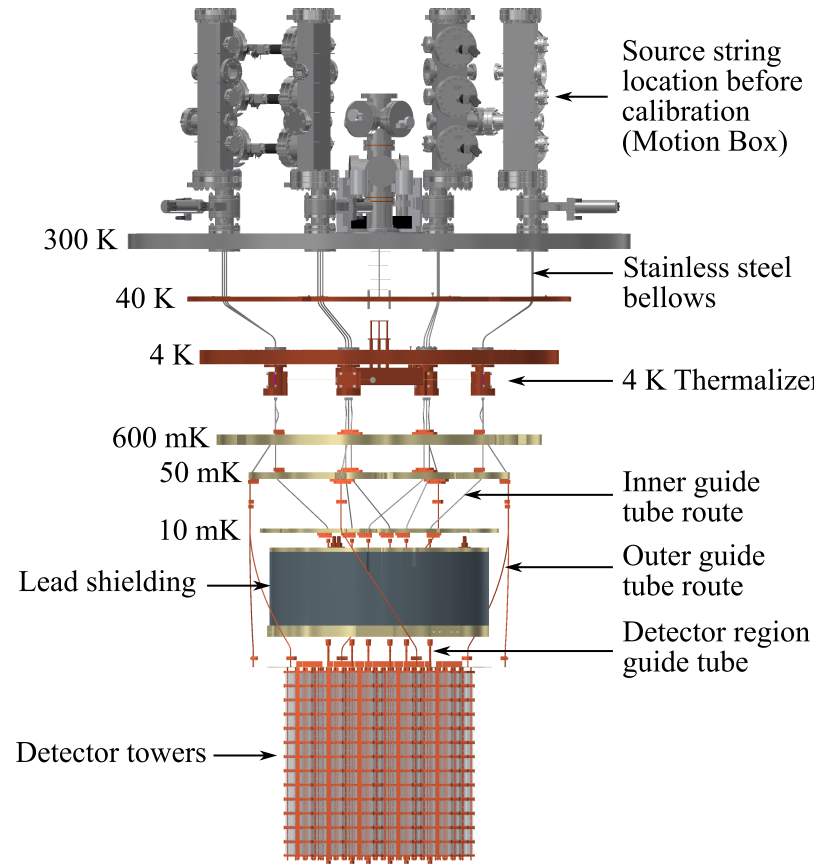
✓ expected to have a discovery sensitivity greater than CUORE-0 + Cuoricino limit in less than one month;

✓ expected discovery sensitivity of $T^{0\nu}_{1/2}$~ 4×10^{25} yr (3σ) in 5 years of live time;

- Bolometers require independent *in situ* energy calibration;
- For CUORE, we use:
  - ^{232}Th γ-ray sources every ~month (239 keV to 2615 keV);
  - Constant-energy pulsers to measure detector stability and correct for variations in detector gain;
- Sources are outside cryostat during physics data-taking and lowered into cryostat and cooled to 10 mK for calibration;
- Sources are put on strings and are lowered under their own weight;
- A series of tubes in the cryostat guides the strings;







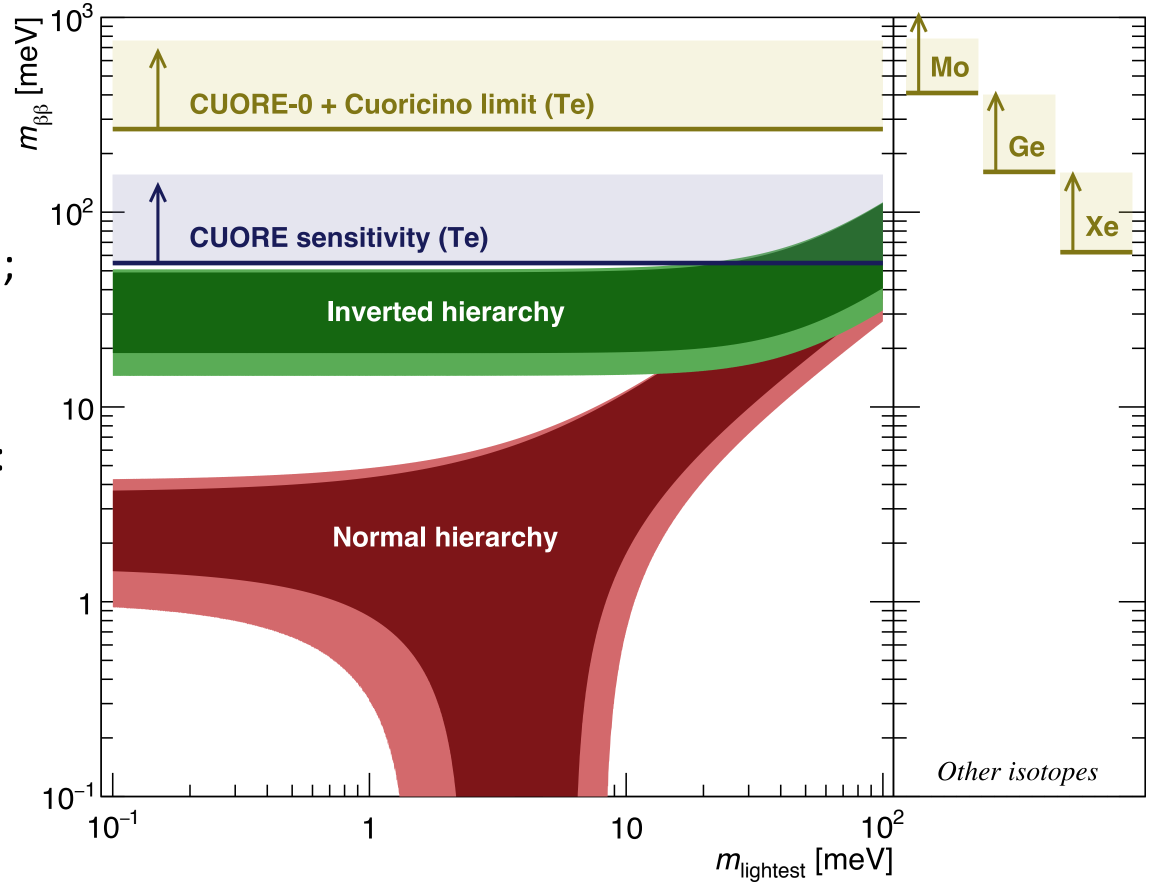
$m_{\beta\beta}$ sensitivity and limits

Assuming:

- BI = 0.01 counts/(keV•kg•yr);
- energy resolution of 5 keV FWHM;
- 5 years live time;

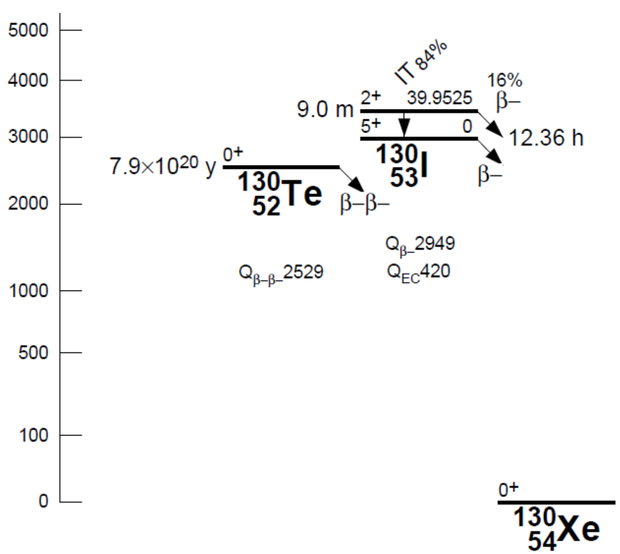
CUORE expected sensitivity to $m_{\beta\beta}$ is:

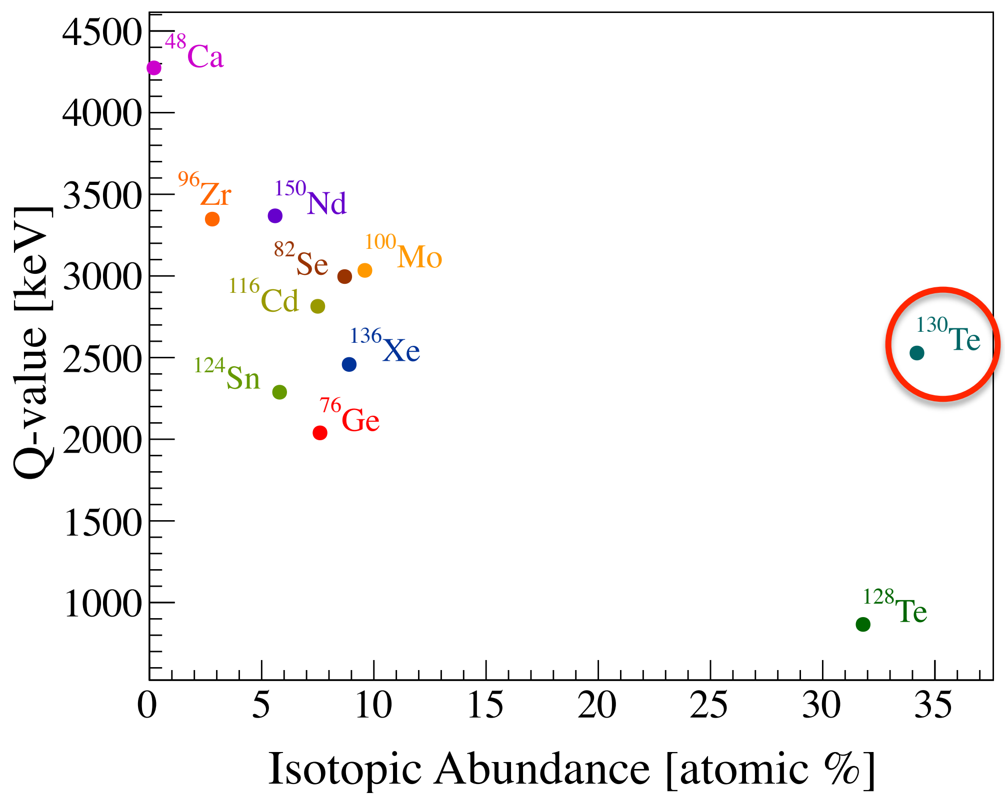
$$m_{\beta\beta} < 50 - 130 \quad meV$$



^{130}Te for 0ν DBD

- good Q-value (2528 keV) in low β/γ region;
- high natural abundance (34.17%);





Roman Lead

- Ancient Roman lead bricks for low-activity shielding;
- Recovered in late ‘80s from shipwreck off Sardinian coast;
- Obtained through agreement between INFN and Italian historical society;
- 270 bricks, 33 kg each = 7 tons (after inscriptions removed);